EFFECTS OF STRESS ON THE PROBABILITY OF DETECTION FOR MAGNETIC FLUX LEAKAGE INSPECTION

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INTRODUCTION

In nondestructive inspection of a part, the accept / reject decision is typically based on the comparison of the measured variable to a threshold value. In a practical test situation various factors introduce randomness and uncertainty in the measurement, thus affecting the accept / reject decision. The concept of probability of detection offers a measure of the capability of nondestructive evaluation methods to detect defects, in the presence of different sources of uncertainties. For instance, it has been previously established [1], that mechanical stress introduces variations in the magnetic flux leakage measurements. Residual stress affects the magnetic properties of ferromagnetic materials and is one of the factor s that can potentially affect the detectability of defects.

This paper describes a scheme for studying the effect of stress on probability of detection (POD) of defects commonly found in transmission pipelines. Magnetic flux leakage is the most widely used NDE technique in natural gas transmission pipeline inspection [2]. This method employs an "intelligent" inspection tool, illustrated on figure 1, which is inserted in the pipeline and is propelled by the gas pressure. The tool magnetizes the pipe-wall and reads the flux leakage field using an array of sensors located along the circumference of the tool. Figure 2 illustrates the flux distribution around an external defect, typically encountered in MFL inspection. The sensors in the inspection tool register and analyze this magnetic flux leakage field.

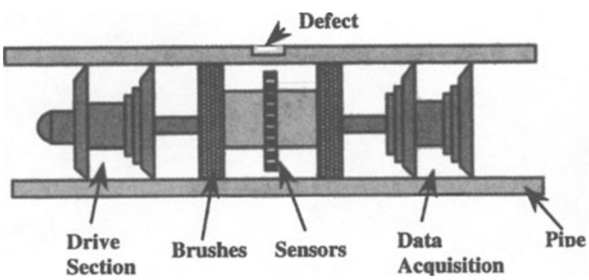

Fig.1 MFL transmission pipeline inspection tool.

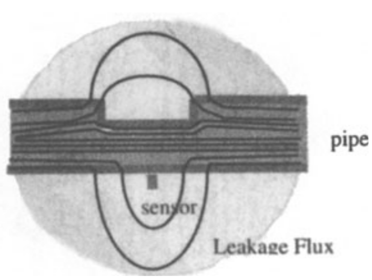

Fig.2 Magnetic flux leakage around a defect.

There are number of factors that affect the readings obtained from the sensors, such as permeability of the pipewall, variable tool velocity, sensor liftoff and orientation, variation in the external magnetization level and the presence of mechanical stress. Consequently flaws of the same size and kind can produce varying MFL signatures, which can result in potential misses of small defects small defects.

A major cause of pipeline failure is mechanical damage, usually caused by external forces such as unstable ground or the operation of construction / excavation equipment. The type of mechanical damage considered in this paper is gouging, which is characterized by a permanent plastic deformation accompanied by wall thinning, coating damage, but no change of the internal diameter of the pipeline. The permanent plastic deformation gives rise to residual stress in the bulk of the material around the defect. The presence of residual stress alters the permeability distribution around the defect, which in turn affects the MFL signature of the defect. Figure 3 illustrates the effects of mechanical damage on the measured signals. The dashed line represents the MFL signature of a metal loss defect, which is removal of metal caused by corrosion and is not accompanied by residual stress. The solid line is the MFL signature, obtained from a gouge with exactly the same shape and dimensions as the metal loss in the presence of residual stress. The objective of this paper is to study the effects of stress on the detectability of mechanical damage defects. The paper uses numerical methods for simulating magnetic flux leakage inspection and for predicting defect signatures. Since numerical methods are in general deterministic in nature, they do not take into account the variabilities associated with inspection and testing carried out in the field. The numerical model is used in a Monte Carlo scheme, where the effect of random perturbations of the parameter of interest is studied.

The overall approach for modeling the effects of stress on POD essentially involves modeling the effects of stress on the MFL signal. A finite element model (FEM) incorporating the effects of stress is developed and used to derive a functional relationship between a measured variable (in this case, the peak of the MFL signal) and the stress level. This functional relationship is employed in calculating the probability density functions (pdfs) of a flaw signal and the background signal without a flaw. These pdfs are used to calculate the POD of the flaw at a known threshold level.

MODELING OF STRESS EFFECTS ON MFL

The effect of stress on the MFL signal is modeled using a two step procedure. First, a 3D structural FEM was developed, representing the loading conditions under which a gouge is

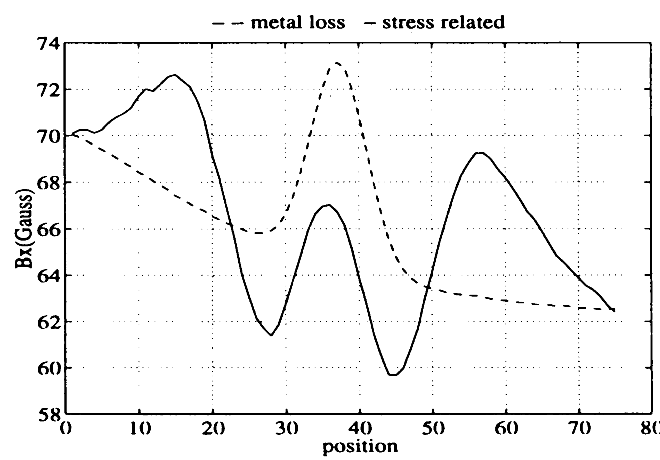

Fig. 3 MFL signals from a metal loss and gouge defects.

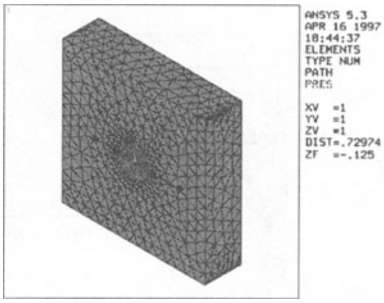

Fig. 4 Finite element model (active).

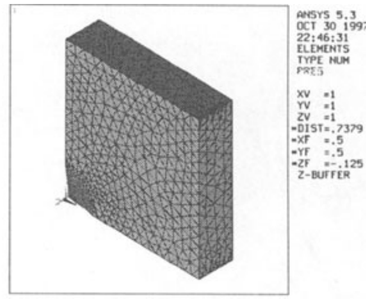

Fig. 5 Finite element model (residual).

produced. Two stress distribution models were considered, both of them simulating a gouge produced by a spherical indentor. The resulting stress distribution was obtained by carrying out structural analysis, using the ANSYS FE solver. In the second step the stress distribution was incorporated into a 3D scalar potential magnetic FEM, by mapping the stress in each element to an appropriate B-H curve. The MFL signature obtained, using the magnetic FEM is related to both the defect geometry and stress condition accompanying it. The details of the two steps are discussed below.

<u>Active Stress Distribution Model</u>

An active stress distribution model represents the field inspection scenario, where the inspection tool measures the MFL of a defect in the presence of an external force, such as a pipe settling on a rock, or being bent by sinking of the supporting structure in soft ground. Figure 4 shows the geometry and FE mesh of a 1" wide, ¼ " thick rectangular 1018 steel plate. The material properties are represented by the Young's modulus ($E=30*10^6$ psi), Poisson's ratio ($v=0.3$) and specific density ($r=0.283$ lb/in^3) of steel. The indentation was simulated by applying pressure on a small spherical pit situated on the top surface of the model. The nodes on the bottom surface of the plate are restrained, to avoid any change in the internal diameter.

<u>Residual Stress Model</u>

The residual stress distribution model simulates the mechanical damage condition caused by a momentary application and removal of an external force, such as a backhoe gouging the pipe – wall. Figure 5 shows the geometry and the FE mesh of the situation. One quarter of the full geometry was modeled, taking into account the symmetry of the problem. The material properties were represented using the true tensile test strain – stress curve for 1020 steel. The nodes on the back of the plate were restrained. Symmetry boundary conditions were applied on the two symmetry planes. The indentation was simulated by a transient pressure applied as shown in Figure 6 on the top surface of the plate. For each loading case, the pressure was linearly increased to some maximal value, representing the load condition, then linearly decreased to zero. The residual stress distribution is obtained after the load has been removed.

Stress is related to strain by:

$$[\sigma]=[D](\varepsilon-\varepsilon^{th}) \tag{1}$$

where, $[\sigma]$ is the stress vector, $[D]$ is the elasticity matrix, $[\varepsilon]$ and $[\varepsilon^{th}]$ are the strain and the thermal strain vectors. The relationship between strains and nodal displacements is given by:

$$\varepsilon=[B]u \tag{2}$$

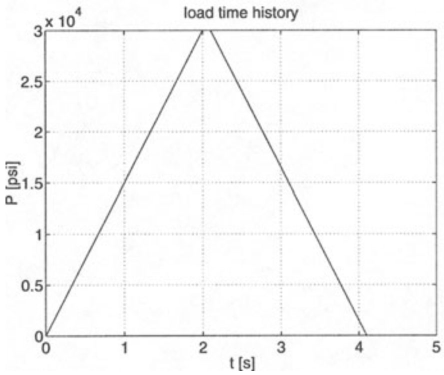

Fig. 6 Load, transient pressure.

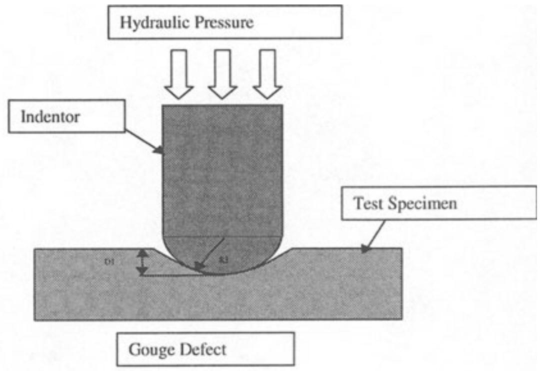

Fig. 7 Machining of a gouge defect.

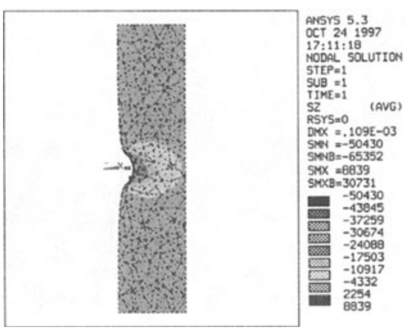

Fig. 8 Stress distribution, active model.

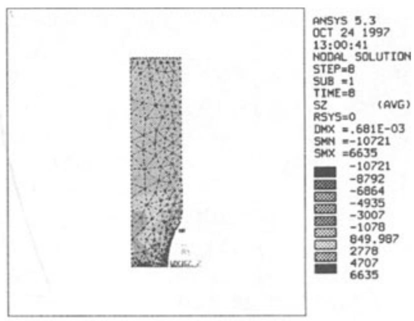

Fig. 9 Stress distribution, residual stress model.

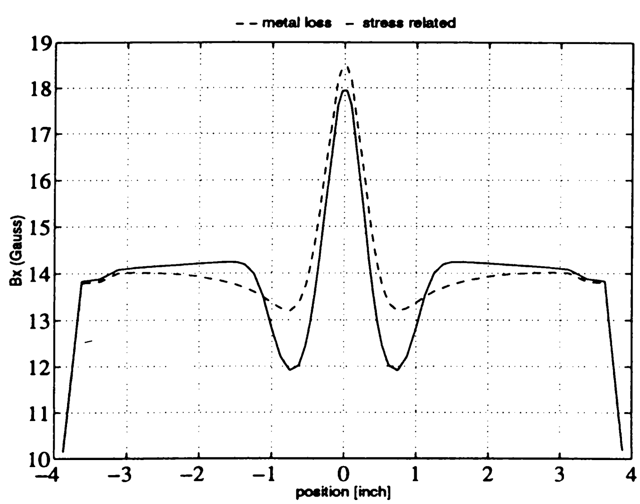

Fig. 10 Effects of active stress on MFL signals.

Figure 8 shows the stress distribution for a gouge, obtained from structural analysis of the active model at 40 klb external load. The stress in the bulk of the material, directly under the defect is mostly compressive in nature. Figure 9 presents the distribution obtained from the residual stress model. It shows large volumes of tensile stress around the defect, with high levels close to the surface opposite to the defect.

Magnetic Model

The magnetic properties of the pipe wall were modeled using three B - H curves, one for unstressed steel $(\sigma = 0)$, the second, corresponding to maximum compression, indexed by $(\sigma = 10)$ and the third in the region of maximum tension indexed by $(\sigma = -10)$. The results of the two structural analysis models were used to assign a unique B-H curve to each element according to its stress level using functional approximation given by [3]:

$$BH(\sigma > 0) = \sigma BH(10) + (1 - \sigma)BH(0) \tag{3}$$
$$BH(\sigma < 0) = (1 - \sigma)BH(0) + \sigma BH(-10) \tag{4}$$

This model was based on the observation that tensile stresses perpendicular to the applied magnetic field and compressive stresses, parallel to the external field result in increased permeability whereas, tensile stresses parallel to the field and compressive stresses perpendicular to the field decrease the permeability [4].

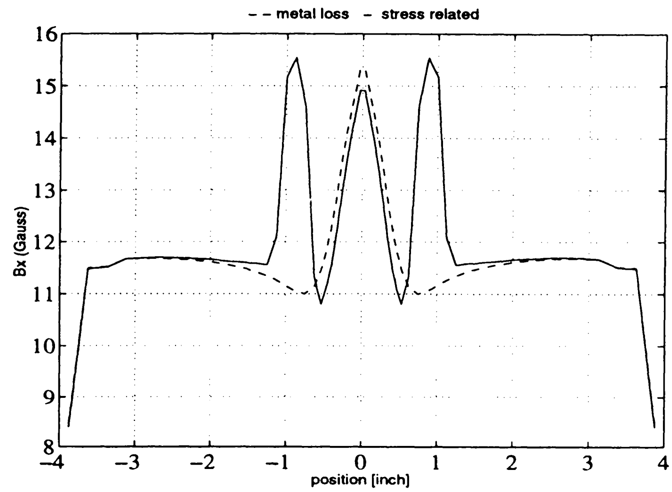

Fig. 11 Effects of residual stress on MFL signals.

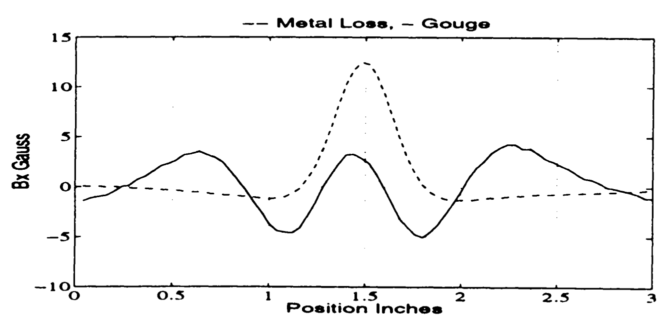

Fig. 12 Experimental gouge and metal loss signals.

PROBABILITY OF DETECTION MODEL

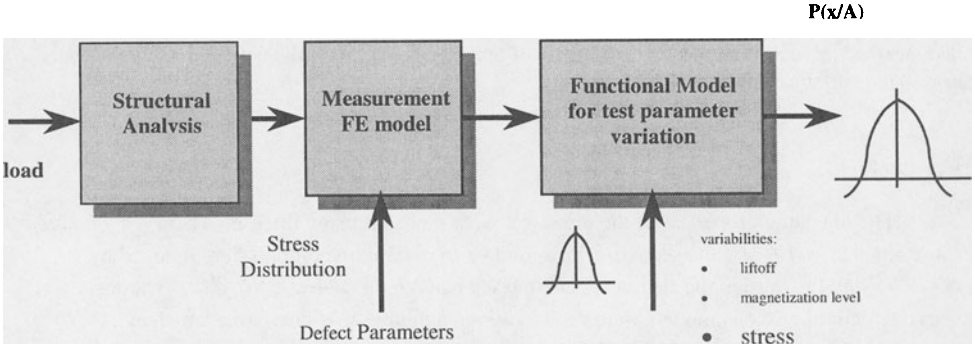

Fig. 13 Schematic of the overall approach for generating signal pdfs.

Figure 10 represents the effects of stress on the measured MFL signal, computed using the active model. Both lines represent the axial component of the MFL signal, for a spherical defect A of radius 0.3125", penetration of 0.5" and depth of 0.125". The dashed line represents the MFL signal obtained at low levels of stress, which is almost identical to a signal obtained from a metal loss defect. The solid line represents the MFL signal at high levels of stress. The decrease of signal level is due to the presence of compressive stresses under the defect, which results in increased permeability. Figure 11 shows the corresponding MFL signals, obtained with the residual stress distribution. The presence of large tensile stresses is seen to increase the flux leakage on both sides of the defect.

Comparison of FE Model and Experimental Results

In order to validate the structural and magnetic models, the numerical signals were compared with experimentally measured MFL signals. Gouges were produced in 1018 steel ¼" thick plate, by applying loads from 10 up to 60 klb on a spherical indentor, as shown in Figure 7. Metal loss defects with the same geometry were machined, using slowly rotating spherical miller. The plates were magnetized, using a yoke magnetizer and the leakage fields around the defects were measured. Figure 12 shows the experimentally obtained MFL signals. The solid line is the signal obtained from a 40 klb gouge and the dashed line is the signal obtained from the corresponding metal loss defect. Comparison with the signals in figure 11 suggests, that the magnetic FE model, with residual stress effects incorporated is an adequate model for studying the effects accompanying mechanical damage.

The approach for calculating the POD with respect to stress is illustrated schematically in Figure 13. In order to evaluate the POD with respect to stress, the measurement model is used to simulate the measurements of the MFL signal for varying stress distributions. The peak of the MFL signal, for a number of values of the parameter representing the stress level in the bulk of the material is used to generate a curve for each defect of interest. The curve serves as a functional model that can be used to generate the conditional pdf of the peak value of the signal in the presence of a flaw p(x/A) by perturbing the stress level. The conditional pdf of the no-flaw signal is obtained from the functional dependency of the peak of the MFL signal on sensor lift – off.

RESULTS AND DISCUSSIONS

Figures 14 and 15 show the functional dependency of the peak MFL signal on the stress level for the active and residual stress models. The variation of the peak of the signal with respect to stress is on the order of 5%. The active stress distribution is mostly compressive in nature and

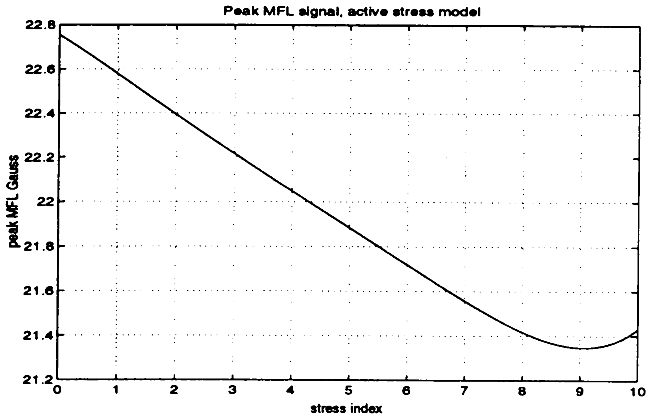

Fig. 14 Peak MFL vs. Stress (active model).

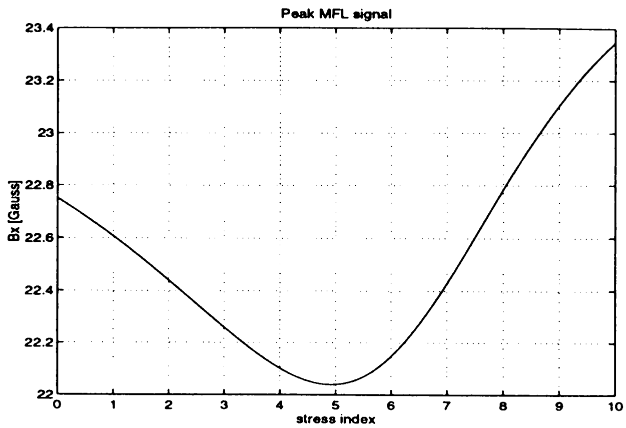

Fig. 15 Peak MFL vs. Stress (residual stress model).

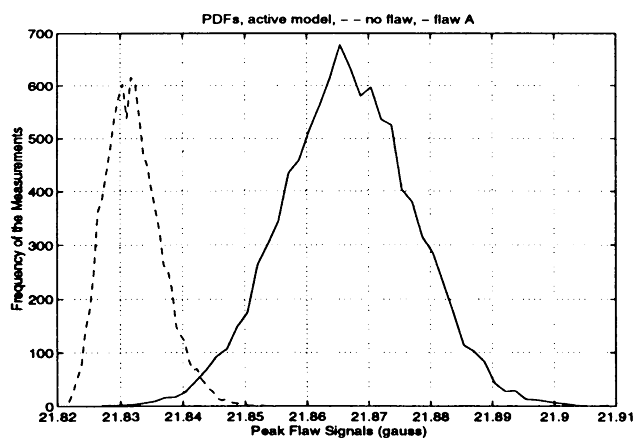

Fig. 16 Conditional pdfs, active stress model.

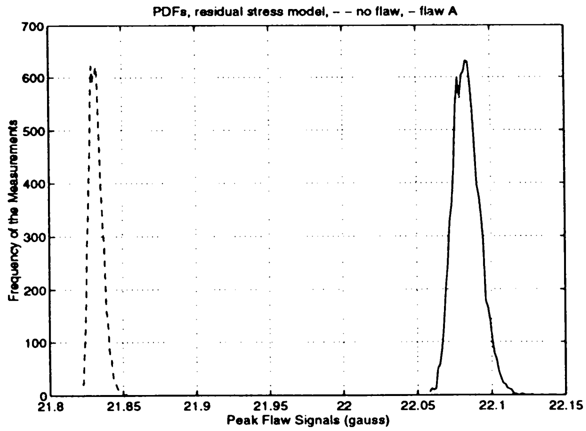

Fig.17 Conditional pdfs, residual stress model.

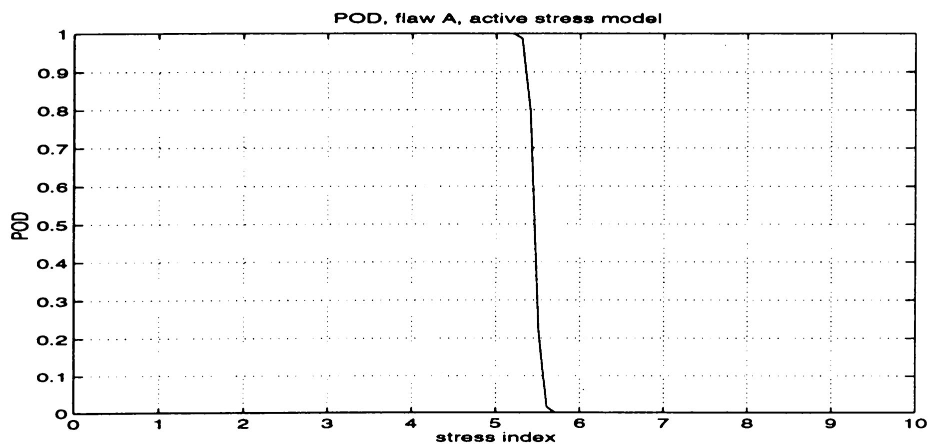

Fig. 18 POD with respect to stress, active model.

therefore an increase of the stress level leads to a decrease of the peak of the MFL signal. The residual stress distribution is characterized with large volumes of tensile stress, therefore, at low levels of stress the peak of the MFL signal is similar to that of a metal loss MFL signal, but at high levels of stress, the peak of the MFL signal increases.

Figures 16 and 17 show the conditional pdfs of a signal in the absence of a flaw, represented by the dashed line and a signal in the presence of a gouge, represented by the solid line. These pdfs were obtained from the active and residual stress models, respectively. Both defect signals simulate flaw A, measured under optimal conditions (external magnetization of 0.9 T and lift off 0.0156"). It can be seen that the conditional pdfs do not overlap, in the case of the residual stress model, which means that residual stresses considered in this study do not affect the detectability of defect A. Figure 18 shows the POD with respect to stress, obtained from the active model. The relationship between POD and stress suggests, that in the presence of "active" stress, flaw A may be rendered impossible to detect, even if measured under optimal conditions.

CONCLUSIONS

This paper presents a scheme for calculating the POD of a flaw with respect to stress in the sample. A structural analysis ANSYS FE model was first used to generate the stress distribution, obtained in the presence of an external load and after removing the load. The stress levels in each element were mapped to a B – H curve, using functional interpolation. A magnetic FE model was used to simulate the MFL inspection signals. Function fitting was used to establish the relationship between stress and peak of the MFL signal.

The conditional pdfs of the flaw and background signals were obtained by randomly perturbing the stress parameter in the functional relationship between stress and the peak of the MFL signal. The use of function fitting reduced the number of FE simulations necessary to compute the pdfs. Furthermore, this reduction did not compromise the accuracy of the results. It was found, that the presence of residual stresses does not affect the detectability of flaw A, when measured under optimal conditions. However, the presence of large "active" stresses can render flaw A impossible to detect, even when measured under optimal conditions, which is mainly due to the fact that the active stresses surrounding the defect are mainly compressive in nature.

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